

4.2 COST ANALYSIS

Operating an efficient and cost-effective manufacturing process with strict control of material and production costs is the goal of every successful company. Fueled by consumer demand for smaller and lighter electronics, rapid and continuous advances in circuit technology make this goal a necessity for PWB manufacturers attempting to compete in today's global marketplace. The higher aspect-ratio holes and tighter circuit patterns on current PWBs are forcing manufacturers to continually evaluate and eventually replace aging manufacturing processes that are unable to keep up with the ever-increasing technology threshold. When coupled with the typically slim profit margins of PWB manufacturers, these process changes represent a major capital investment to a company and emphasize the importance of selecting an efficient, cost-effective process that will allow the company to remain competitive. As a result, manufacturers are seeking comprehensive and more detailed cost data before investing in alternative processes.

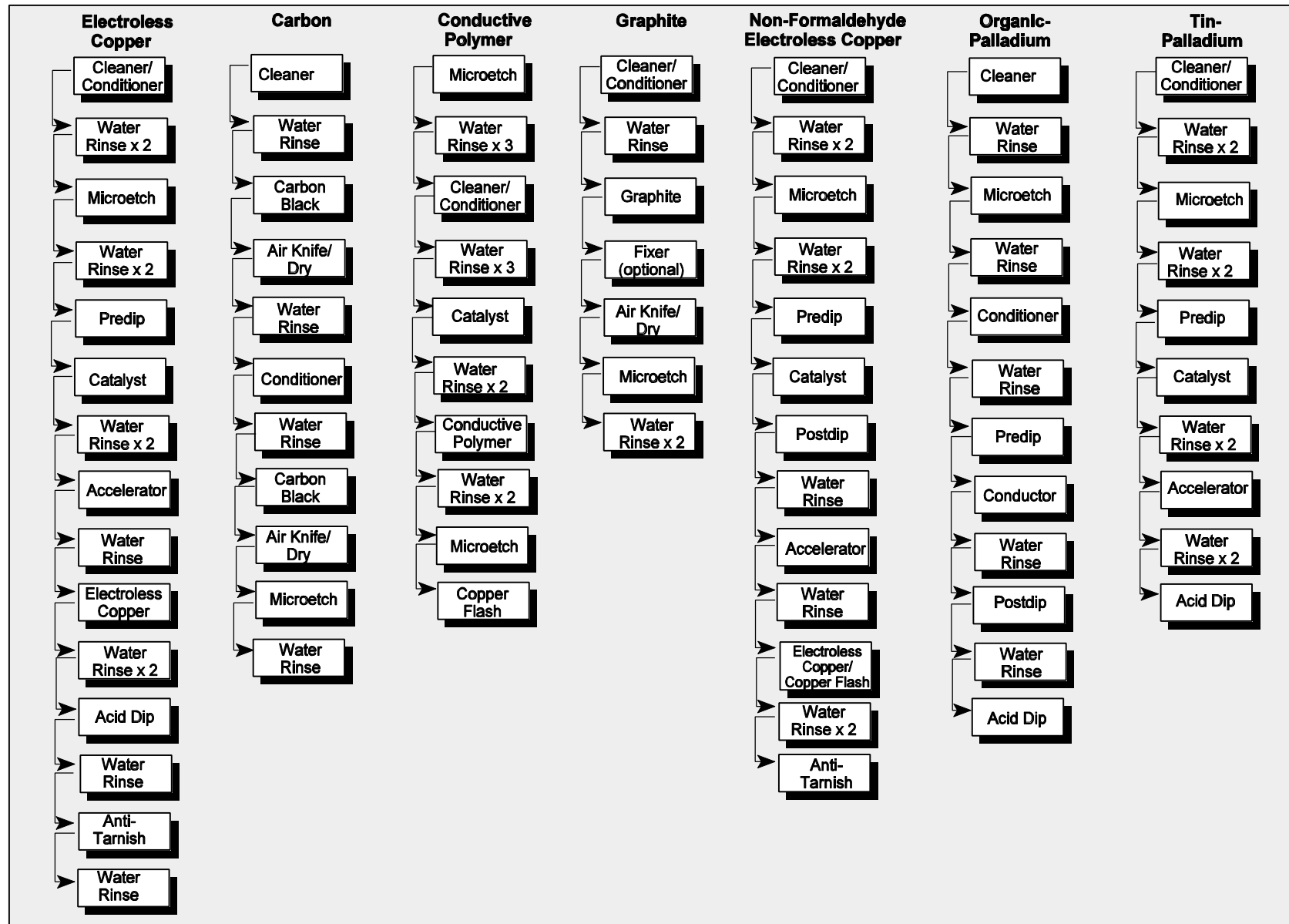
This section presents a comparative cost analysis of the MHC technologies. Costs were developed for each technology and equipment configuration (vertical, immersion-type equipment, or horizontal, conveyorized equipment) for which data were available from the IPC Workplace Practices Questionnaire and Performance Demonstration. Table 4.13 presents the processes (alternatives and equipment configurations) evaluated.

Table 4.13 MHC Processes Evaluated in the Cost Analysis

MHC Alternative	Non-Conveyorized	Conveyorized
Electroless Copper	✓	✓
Carbon		✓
Conductive Polymer		✓
Graphite		✓
Non-Formaldehyde Electroless Copper	✓	
Organic-Palladium	✓	✓
Tin-Palladium	✓	✓

Costs were analyzed using a cost model developed by the University of Tennessee Department of Industrial Engineering. The model employs generic process steps and functional groups (see Section 2.1, Chemistry and Process Description of MHC Technologies) and typical bath sequences (see Section 3.1, Source Release Assessment) for each process alternative. Figure 4.13 presents the generic process steps and typical bath sequences. To develop comparative costs on a \$/surface square foot (ssf) basis, the cost model was formulated to calculate the cost of performing the MHC function on a job consisting of 350,000 ssf. This is the average annual throughput for facilities in the IPC Workplace Practices Questionnaire database. The cost for each process is compared to a generic non-conveyorized electroless copper process, defined here as the baseline process.

Figure 4.13 Generic Process Steps and Typical Bath Sequences of MHC Technologies



The overall objective of this analysis was to determine the comparative costs of the MHC technologies using a cost model that adheres to fundamental principles of cost analysis. Other objectives were to make the analysis flexible and to consider environmental costs. The cost model was designed to estimate the comparative costs of fully operational MHC process lines. It does not estimate start-up costs for a facility switching to an alternative MHC technology or the cost of other process changes that may be required to implement a new MHC technology. Section 4.2.1 gives an overview of the cost methodology. Section 4.2.2 presents simulation model results. Section 4.2.3 describes details of the cost methodology and presents sample cost calculations. Section 4.2.4 contains analysis results, while Section 4.2.5 presents a sensitivity analysis of the results. Section 4.2.6 presents conclusions.

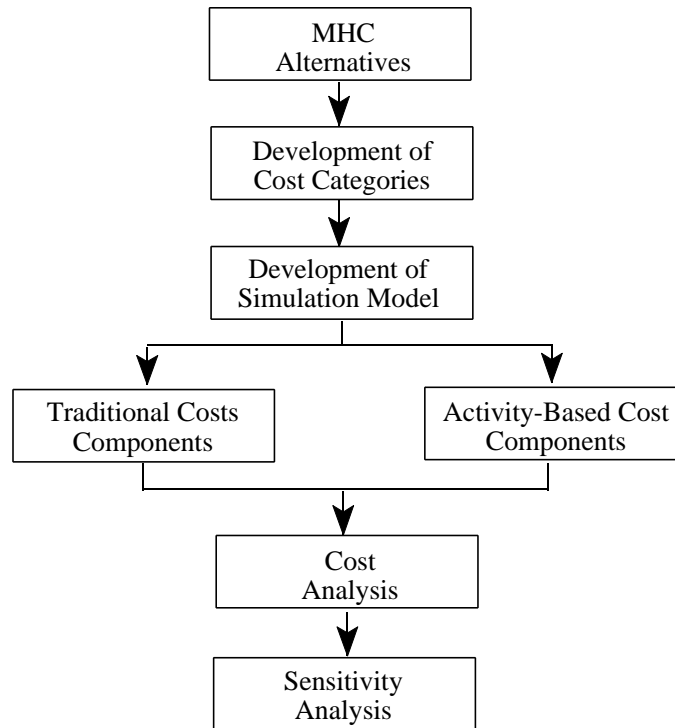
4.2.1 Overview of the Cost Methodology

The costs of the MHC technologies were developed by identifying the steps in each process, breaking each step down into its cost components, and determining the cost of each component. Component costs were determined utilizing traditional costing mechanisms, computer simulation, and ABC. Computer simulation was used to replicate each of the MHC processes to determine the time required to complete the specified job and other job-specific metrics. ABC is a cost accounting method that allocates indirect or overhead costs to the products or processes that actually incur those costs. Activity-based costs are determined by developing bills of activities (BOAs) for tasks essential to the process. A BOA is a listing of the component activities involved in the performance of a certain task, together with the number of times each component activity is performed. The BOA determines the cost of a task by considering the sequence of actions and the resources utilized while performing that task.

Framework for the Cost Formulation

Figure 4.14 presents the hybrid cost formulation framework used in this analysis. The first step in the framework was to develop or define the alternatives to be evaluated. The generic process descriptions, chemical baths, typical bath sequences, and equipment configurations were defined in Table 4.13 and Figure 4.13. This information was used to identify critical variables and cost categories that needed to be accounted for in the cost analysis. Cost categories were analyzed to identify the data required to calculate the costs (i.e., unit costs, utilization or consumption rates, criteria for performing an activity, such as chemical bath replacement, the number of times an activity is performed, etc.). For each process, a computer simulation was then developed using ARENA® computer simulation software and information derived from the cost components. The simulations were designed to model a MHC manufacturing job consisting of 350,000 ssf.

Figure 4.14 Hybrid Cost Formulation Framework



Simulation modeling provides a number of advantages to the cost analysis, including the following:

- Simulation modeling can replicate a production run on the computer screen, allowing an analyst to observe a process when the actual process does not exist. In this case, the generic MHC technologies, as they are defined in Figure 4.13, may not exist within any one facility.
- Simulation allows for process-based modifications and variations, resulting in inherent flexibility within the system. Simulation models can be designed to vary the sequence of operations, add or delete operations, or change process times associated with operations, materials flows, and other variables.
- Data gathered from PWB manufacturers, chemical suppliers, and the Performance Demonstration have some data gaps and inconsistencies. However, these data must be aggregated to develop comparative costs of the generic MHC alternatives. Thus, data collected from one or more facilities may not fully represent a generic MHC alternative or group of alternatives. Process simulation based on fundamental assumptions and data helps clear up data inconsistencies and fill data gaps.
- Simulation enables one to study the sensitivity of critical performance measures to changes in underlying input variables. Constant input variables may be modified in the sensitivity analysis to determine the uncertainty (in terms of probability distributions) associated with these input variables.

Direct results of the simulation model and results derived from simulation outputs include the following:

- The amount of time the MHC line operates to produce the job.
- The number of times an activity is performed during the course of the job.
- Consumption rates (e.g., water, energy, and chemical consumption).
- Production rates (e.g., wastewater generation).

Simulation results were combined with traditional cost components to adjust these costs for the specified job. An example of this is the determination of equipment cost. Simulation results were used to calculate a utilization ratio (UR), defined as the amount of time in days required to produce 350,000 ssf divided by one operating year (defined as 250 days). Annualized equipment costs were determined utilizing industry sources for equipment price and depreciation guidelines from the Internal Revenue Service. These costs were multiplied by the UR to determine the equipment costs for the job being evaluated.

Activity-based costs were determined by combining simulation results for the frequency of activities with the cost of an activity developed on a BOA. For example, the activity costs of replacing a particular bath were determined by developing a BOA, developing costs for each activity on the BOA, and multiplying these costs by the number of bath replacements required to complete a job of 350,000 ssf. In this manner, the overall analysis combines traditional costs with simulation outputs and activity-based costs. The effects of critical variables on the overall costs were then evaluated using sensitivity analysis.

Cost Categories

Table 4.14 summarizes the cost components considered in this analysis, gives a brief description of each cost component and key assumptions, and lists the primary sources of data for determining the costs. Section 4.2.3 gives a more detailed accounting of the cost components, including sample cost calculations for each component.

In addition to traditional costs, such as capital, production, and maintenance costs, the cost formulation identifies and captures some environmental costs associated with the alternatives. In this regard, both simulation and ABC assist in analyzing the impact of the MHC alternatives on the environment. Specifically, the amounts of energy and water consumed as well as the amount of wastewater generated are determined for each MHC alternative. Environmental costs that could not be quantified include wastewater treatment and solid waste disposal costs. Also, the costs of defective boards and the consequent waste of resources were not quantified. These costs are discussed in more detail, below.

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Table 4.14 Cost Components

Cost Category	Component	Description of Cost Component	Sources of Cost Data
Capital Cost	Primary Equipment	Annualized cost of equipment with throughput capacity of 100 panels/hr times UR ^a ; assumes 10 year equipment life and straight-line depreciation.	Vendor quote for equipment cost; time to complete job from simulation.
	Installation	Annualized cost of delivering and installing equipment times UR ^a ; assumes 10 year equipment life and straight-line depreciation.	Vendor quote for installation costs; time to complete job from simulation.
	Facility	Annualized cost of floor space required to operate MHC equipment times UR ^a ; assumes 25 year facility life and straight-line depreciation.	Floor space requirements from Workplace Practices Survey; unit cost for industrial floor space from published sources.
Material Cost	Process Chemicals	Costs of chemicals used in initial bath setup and to replace spent process baths.	Vendor quotes for chemical product cost; bath sizes from Workplace Practices Survey; bath replacement criteria from supplier data; number of bath replacements required for job from simulation.
Utility Cost	Water	Water consumption costs based on number of rinse tanks per process line; daily water usage per tank, and days to complete job.	Number of rinse tanks and daily water usage per tank from Section 5.1, Resource Conservation; days to complete job from simulation.
	Electricity	Electricity costs based on daily electricity consumption by MHC equipment and days to complete job.	Daily electricity consumption from Section 5.2, Energy Impacts; days to complete job from simulation.
	Natural Gas	Natural gas consumption based on daily natural gas consumption from drying ovens (carbon and graphite processes only) and days to complete job.	Daily natural gas consumption from Section 5.2, Energy Impacts; days to complete job from simulation.
Wastewater Cost	POTW Permit	Cost for permit to discharge wastewater to publicly-owned treatment works (POTW).	Not quantified; assumed to be the same for all alternatives.
	Wastewater Pretreatment Cost	Cost to pretreat wastewater prior to discharge to POTW.	Not quantified; pretreatment costs are expected to differ significantly among the alternatives, but insufficient data were available to reliably estimate these costs.
	Wastewater Discharge Costs	Fees for wastewater discharge assessed by local utility.	Quantity of wastewater discharged assumed equal to water usage; discharge fees based on fees charged by Knoxville, Tennessee Utility Board (KUB).

Cost Category	Component	Description of Cost Component	Sources of Cost Data
Production Cost	Labor	Labor costs for line operator, excluding labor costs for maintenance activities (included under maintenance costs). Assumes one line operator per day per conveyORIZED process, 1.1 line operators per day per non-conveyORIZED process.	Number of line operators based on Workplace Practices Survey data and site visits; days to produce job from simulation; labor rate = \$10.22/hr based on published data.
	Transportation of Materials	Cost to transport chemicals required for bath replacement from storage to process line.	Cost of transporting materials from BOA; number of bath replacements required from simulation.
Maintenance Cost	Bath Clean-up	Labor and materials (excluding replacement chemicals) costs to clean up a chemical tank during bath replacement.	Cost to clean up tank from BOA; number of bath cleanups (replacements) required from simulation.
	Bath Setup	Labor and equipment costs to set up a chemical tank after bath replacement.	Cost to set up bath from BOA; number of bath setups required from simulation.
	Sampling and Analysis	Labor and materials costs for sampling and analysis of chemical baths.	Assumes analytical work done in-house. Cost for one activity from BOA; annual number of samples from Workplace Practices Survey adjusted using UR ^a .
	Filter Replacement	Labor costs for replacing bath filters.	Labor cost for one activity from BOA; annual number of filters replaced from Workplace Practices Survey adjusted using UR ^a .
Waste Disposal Cost	Sludge Disposal	Disposal cost to recycle or dispose of sludge from wastewater treatment.	Not quantified; sludge disposal costs are expected to differ significantly among the alternatives, but insufficient data were available to reliably estimate these costs. Factors affecting sludge disposal cost include the characteristics of the sludge (i.e., metal content, percent solids, waste classification, etc.) and the amount of sludge generated.
	Filter Disposal	Disposal cost to recycle or dispose of bath filters.	Not quantified; filter disposal costs are expected to differ significantly among the alternatives, but insufficient data were available to reliably estimate these costs. Factors affecting filter disposal cost include the waste classification of the filter, the size (weight and volume) of the filter, and the number of waste filters generated.
Quality Cost	Defective Boards	Costs of defective boards due to failure of MHC process lines to adequately make holes conductive.	Not quantified; assumed equal among the alternatives. Performance Demonstration showed that all alternatives can work at least as well as the baseline process as long as they are operated according to supplier specifications.

^a UR = utilization ratio = the time in days required to process 350,000 ssf ÷ one operating year (250 days).

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Wastewater Treatment and Sludge Disposal Costs. PWB manufacturing consists of a number of process steps (see Section 1.2.3 for an overview of rigid multi-layer PWB manufacturing). In addition to the MHC process line, these steps include electroplating operations and other steps which consume large quantities of rinse water and, consequently, generate large quantities of wastewater. Most PWB manufacturers combine the effluents from various process lines into one wastewater stream which is treated on-site in a continuous process prior to discharge. As part of the *Pollution Prevention and Control Survey* (EPA, 1995a), PWB manufacturers were asked to provide the following about their on-site wastewater treatment facility:

- A process flow diagram for wastewater treatment.
- The quantity of sludge generated from wastewater treatment.
- The percent solids of the sludge.
- The costs of on-site wastewater treatment.
- The method and costs of sludge recycle and disposal.

Capital costs for wastewater treatment ranged from \$1.2 million for a system purchased in 1980 with a capacity of 135 gallons per minute (gpm) to \$4,000 for a system purchased in 1987 with a capacity of nine gpm. Costs for operating an on-site wastewater treatment system were as high as 3.1 percent of total annual sales. The median cost for wastewater treatment operation was 0.83 percent and the average was 1.02 percent of annual sales.

Wastewater treatment sludges from PWB electroplating operations are classified as an F006 hazardous waste under the Resources Conservation and Recovery Act (RCRA); most facilities combine effluents from the electroplating line with other process wastewaters. Eighty-eight percent of respondents to the Survey reported that wastewater treatment sludges are sent to an off-site recycling facility to recover the metals. The average and median costs for off-site recovery of sludge were \$0.48/lb and \$0.21/lb, respectively. In general, the lower costs experienced by some respondents compared to others were due to larger-size shipments and shorter distances to the recycling sites. In some cases, respondents whose sludge had a higher solids content also reported lower costs; dewatered sludge has a higher recovery value.

Eighty-six percent of Survey respondents used an electroless copper MHC process, 14 percent used a palladium-based process (the Survey did not distinguish between tin- and organic-palladium processes), and one respondent used a graphite process. None of the other MHC alternatives were represented in the Survey.

The IPC Workplace Practices Questionnaire attempted to characterize costs by collecting information about the percent the MHC line contributes to overall wastewater and sludge generation rates. However, most manufacturers were unable to provide this information and the data that were reported were of variable to poor quality.

Since the MHC line is only one of several process lines that discharge effluent to wastewater treatment and because little or no information is available on the contribution of the MHC line to overall wastewater effluents, on-site wastewater treatment and sludge disposal costs could not be reliably estimated. However, costs of wastewater treatment and sludge disposal are expected to differ significantly among the alternatives. For example, the presence of the chelator

EDTA in electroless copper wastewater discharges makes these effluents more difficult to treat. However, complexing agents, such as the ammonia found in other PWB manufacturing steps, also adversely affect the treatability of wastewater.

Other Solid Waste Disposal Costs. Two other types of solid wastes were identified that could have significantly different waste disposal costs among the alternatives: filter disposal cost and defective boards disposal costs. Table 4.15 presents the number of filters that would be replaced in each process during a job of 350,000 ssf. These data are based on data from the IPC Workplace Practices Questionnaire and a UR calculated for each process from simulation results. (Simulation results are discussed further in Section 4.2.2.) While these results illustrate that the number of waste filters generated by the alternatives differ significantly, no information is available on the characteristics of the filters used in alternative processes. For example, the volume or mass of the filters and waste classification of the filters (hazardous or non-hazardous) would significantly affect the unit cost for disposal. Therefore, filter disposal costs were not estimated.

Table 4.15 Number of Filter Replacements by MHC Process

MHC Process	Filter Replacements per Year ^a	Filter Replacements per Job ^b
Electroless Copper, non-conveyorized (BASELINE)	100	160
Electroless Copper, conveyorized	100	35
Carbon, conveyorized	20	7
Graphite, conveyorized	103	52
Conductive Polymer, conveyorized	74	21
Non-Formaldehyde Electroless Copper, non-conveyorized	17	12
Organic-Palladium, non-conveyorized	50	22
Organic-Palladium, conveyorized	50	16
Tin-Palladium, non-conveyorized	74	35
Tin-Palladium, conveyorized	74	19

^a 90th percentile data based on Workplace Practices Survey data. Data not adjusted for throughput or to account for differing maintenance policies at individual PWB manufacturing facilities.

^b Based on simulation results for a job of 350,000 ssf.

The number of defective boards produced by an alternative has significance not only from the standpoint of quality costs, but also from the standpoint of waste disposal costs. Clearly, a higher defect rate leads to higher scrap and, therefore, waste of resources. However, the Performance Demonstration showed that each of the alternatives can perform as well as the electroless copper process if operated according to specifications. Thus, for the purposes of this analysis, no differences would be expected in the defect rate or associated costs of the alternatives.

Simulation Model Assumptions and Input Values

Appendix G presents a graphic representation of the simulation models developed for each of the MHC alternatives. The assumptions used to develop the simulation models and

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model input values are discussed below.

Assumptions. Several assumptions used in the simulation model are based on the characteristics of a model facility presented in the Source Release Assessment and Exposure Assessment (Sections 3.1 and 3.2, respectively). Assumptions include the following:

- The facility operates an MHC line 250 days/year, one shift/day. Many facilities operate two shifts, but the Exposure Assessment and this analysis use first shift data as representative. This assumption could tend to underestimate labor costs for companies that pay higher rates to second shift workers. Or it could tend to overestimate equipment costs for a company running two shifts and using equipment more efficiently. However, since this assumption is used consistently across alternatives, the effects on the comparative cost results are expected to be minor.
- The MHC process line operates an average of 6.8 hrs/shift.
- The MHC line is down at least 1.2 hours per day for start-up time and for maintenance, including lubricating of equipment, sampling of baths, and filter replacement.
- Additional down time occurs when the MHC line is shut down to replace a spent or contaminated bath.
- PWB panels that have been processed up to the MHC step are available whenever the MHC process line is ready for panels.
- If a chemical bath is replaced at the end of the day, such that the amount of time required to replace the bath exceeds the time remaining in the shift hours, employees will stay after hours and have the bath ready by the beginning of the next shift.
- The entire MHC process line is shut down whenever a bath requires replacing, but partially processed racks or panels are finished before the line is shut down.
- The MHC process only shuts down at the end of a shift and for bath replacement.
- The process is empty of all panels or racks at the end of each shift and starts the process empty at the beginning of a shift.

Further simulation assumptions have to be defined separately for conveyORIZED and non-conveyORIZED systems. ConveyORIZED MHC process assumptions are as follows:

- The size of a panel is 17.7" x 22.9" (from IPC Workplace Practices Questionnaire data for conveyORIZED processes).
- Panels are placed on the conveyor whenever space on the conveyor is available, and each panel requires 18" (including space between panels).
- Conveyor speed is constant, thus, the volume (gallons) of chemicals in a bath varies by bath type (i.e., microetch, conditioner, etc.) and with the length of the process step (e.g., bath or rinse tank) to provide the necessary contact time (see Table 4.16 for bath volumes).
- The conveyor speed, cycle time, and process down time are critical factors that determine the time to complete a job.

Table 4.16 Bath Volumes Used for Conveyorized Processes

Chemical Bath	Bath Volume by MHC Alternative (gallons)					
	Electroless Copper	Carbon	Conductive Polymer	Graphite	Organic-Palladium	Tin-Palladium
Cleaner/Conditioner	65	NA	65	65	NA	65
Cleaner	NA	44	NA	NA	44	NA
Carbon	NA	128	NA	NA	NA	NA
Graphite	NA	NA	NA	37	NA	NA
Conditioner	NA	56	NA	NA	56	NA
Polymer	NA	NA	26	NA	NA	NA
Microetch	64	64	64	64	64	64
Predip	50	NA	NA	NA	50	59
Catalyst	139	NA	139	NA	NA	139
Accelerator	80	NA	NA	NA	NA	80
Conductor	NA	NA	NA	NA	108	NA
Electroless Copper	185	NA	NA	NA	NA	NA
Post Dip	NA	NA	NA	NA	45	NA
Acid Dip	79	NA	NA	NA	79	79
Anti-Tarnish	39	NA	NA	NA	NA	NA

NA: Not Applicable.

Non-conveyorized MHC process assumptions are as follows:

- The average volume of a chemical bath is 75 gallons (from IPC Workplace Practices Questionnaire data for non-conveyorized processes).
- Only one rack of panels can be placed in a bath at any one time.
- A rack contains 20 panels (based on IPC Workplace Practices Questionnaire data, including the dimensions of a bath, the size of a panel, and the average distance between panels in a rack).
- The size of a panel is 16.2" x 21.5" to give 96.8 ssf per rack.
- The frequency at which racks are entered into the process is dependent upon the bottleneck or rate limiting step.
- The duration of the rate limiting step, cycle time, and process down time are critical factors that determine the time to complete a job.

Inputs Values. Input values for the critical factors identified above (cycle time, down time, and conveyor speed for conveyorized processes, and cycle time, down time, and duration of rate limiting step for non-conveyorized processes) were developed from IPC Workplace Practices Questionnaire data and Product Data Sheets prepared by suppliers which describe how to mix and maintain chemical baths. Tables 4.17 and 4.18 present time-related inputs to the simulation models for non-conveyorized and conveyorized processes, respectively.

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Table 4.17 Time-Related Input Values for Non-Conveyorized Processes^a

Non-Conveyorized MHC Alternative	Time Required to Replace a Bath ^b (minutes)	Rate Limiting Bath	Time in Rate Limiting Bath ^c (minutes)	Process Cycle Time ^c (minutes)
Electroless Copper	180	Electroless Copper	34	48
Non-Formaldehyde Electroless Copper	30	Electroless Copper	16	51
Organic-Palladium	180	Accelerator	9.2	30
Tin-Palladium	108	Conductor	5.3	52

^a Values are averages or 90th percentile data from the IPC Workplace Practices Questionnaire and may represent chemical products from more than one supplier. For example, five suppliers of electroless copper chemical products participated in the project. Input values may underestimate or overestimate those of any one facility, depending on factors such as individual operating procedures, the chemical or equipment supplier, and the chemical product used.

^b 90th percentile value used in the Exposure Assessment from IPC Workplace Practices Questionnaire data (see Section 3.2). Used to calculate down time.

^c Average values from the IPC Workplace Practices Questionnaire.

Table 4.18 Time-Related Input Values for Conveyorized Processes^a

Conveyorized MHC Alternative	Time Required to Replace a Bath ^b (minutes)	Length of Conveyor ^c (feet)	Process Cycle Time ^c (minutes)	Conveyor Speed ^d (ft/min)
Electroless Copper	180	71	15	4.7
Carbon	180	31	13	2.4
Conductive Polymer	180	34	8.0	4.3
Graphite	219	27	7.8	3.5
Organic-Palladium	108	50	15	3.3
Tin-Palladium	180	47	8.6	5.5

^a Values are averages or 90th percentile data from the IPC Workplace Practices Questionnaire and may represent chemical products from more than one supplier. For example, five suppliers of electroless copper chemical products participated in the project. Input values may underestimate or overestimate those of any one facility, depending on factors such as individual operating procedures, the chemical or equipment supplier, and the chemical product used.

^b 90th percentile value used in the Exposure Assessment from IPC Workplace Practices Questionnaire data (see Section 3.2). Used to calculate down time.

^c Average values from IPC Workplace Practices Questionnaire.

^d Conveyor speed = length of conveyor ÷ process cycle time.

The input values for the time required to replace a bath time (in Tables 4.17 and 4.18) are used together with bath replacement criteria in the calculation of down time. Suppliers provide instructions with their products (called Product Data Sheets for the purposes of this project) that describe when a bath should be replaced because it is expected to be spent or too contaminated to be used. These replacement criteria are usually given in one of three forms:

- As a bath capacity in units of ssf per gallon of bath.
- As a concentration-based criterion that specifies an upper concentration limit for contaminants in the bath, such as grams of copper per liter in the microetch bath.
- As elapsed time since bath creation.

Bath replacement criteria submitted by suppliers were supplemented with IPC Workplace Practices Questionnaire data and reviewed to determine average criteria for use in the simulation models. Criteria in units of ssf/gallon were preferred because these can be correlated directly to the volume of a bath. Once criteria in ssf/gallon were determined, these were converted to units of racks per bath replacement for non-conveyorized processes and panels per bath replacement for conveyorized processes. The converted values were used as inputs to the simulation models. As an example, Table 4.19 presents bath replacement criteria used to calculate input values for electroless copper processes. Appendix G presents the different bath replacement criteria recommended by chemical suppliers, and the input values used in this analysis.

Table 4.19 Bath Replacement Criteria for Electroless Copper Processes

Chemical Bath	Bath Replacement Criteria^a (ssf/gal)
Cleaner/Conditioner	510
Microetch	250
Predip	540
Catalyst	Replace once per year
Accelerator	280
Electroless Copper	430
Acid Dip	675
Anti-Tarnish	325

^a Values were selected from data provided by more than one electroless copper chemical supplier. To convert to units of racks per bath replacement for non-conveyorized processes, multiply by 75 gallons (the average bath size) and divide by 96.8 ssf (ssf per rack). To convert to units of panels per bath replacement for conveyorized processes, multiply by the bath size in gallons and divide by 5.6 ssf/panel.

Activity-Based Costing (ABC)

As discussed previously, ABC is a method of allocating indirect or overhead costs to the products or processes that actually incur those costs. Activity-based costs are determined by developing BOAs for critical tasks. A BOA is a listing of the component activities involved in the performance of a certain task, together with the number of times each component activity is performed. The BOA determines the cost of a task by considering the sequence of actions and the resources utilized while performing that task. In this analysis, the costs of critical tasks determined by a BOA are combined with the number of times a critical task is performed, derived from simulation results to determine the total costs of that activity.

BOAs were developed for the following critical tasks performed within MHC alternatives:

- Chemical transport from storage to the MHC process.
- Tank cleanup.
- Bath setup.
- Bath sampling and analysis.

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- Filter replacement.

These BOAs were developed based on information developed for earlier projects involving similar tasks and on information gathered through site visits and general process knowledge. The following discussion uses the BOA for chemical transport, presented in Table 4.20, as an example of how BOAs were developed and used. Appendix G presents the BOAs for other activities.

Key assumptions were developed to set the limits and to designate the critical activity's characteristics. For chemical transport, the assumptions were:

- Chemical costs are not included in the BOA, but are considered within material costs.
- The portion of labor costs considered are not included within production costs.
- Labor rate used is \$10.22 per hour, consistent with the labor rate for an operator level job.
- Multiple chemicals are required for each bath replacement.
- All chemicals for a bath replacement are transported on one forklift trip.
- Chemicals are purchased in containers larger than the line containers used to move chemicals to the MHC process.
- All chemicals are stored in a central storage location.
- Chemicals are maintained in central storage via inventory tracking and physical monitoring.
- A forklift costs \$580/month or \$0.06/minute, including leasing, maintenance, and fuel.
- Forklifts are utilized to move all chemicals.
- Forklifts are parked in an assigned area when not in use.

Each critical task was broken down into primary and secondary activities. For chemical transport, the six primary activities are: paperwork associated with chemical transfer, moving forklift to chemical storage area, locating chemicals in storage area, preparation of chemicals for transfer, transporting chemicals to MHC process, and transporting chemicals from MHC process to actual bath. The secondary activities for the primary activity of "transport chemicals to MHC process" are: move forklift with chemicals, unload line containers, and park forklift in assigned parking area. For each secondary activity the labor, material, and forklift costs are calculated. The sum of the costs of a set of secondary activities equals the cost of the primary activity. The forklift costs are a function of the time that labor and the forklift are used.

For example, for a chemical transport activity that requires two minutes, the labor cost is \$0.34 (based on a labor rate of \$10.22 per hour) and the forklift cost is \$0.12 (based on \$0.06 per minute). Materials costs are determined for materials other than chemicals and tools required for an activity. The total of \$9.11 in Table 4.20 represents the cost of a single act of transporting chemicals to the MHC line. The same BOAs are used for all MHC technologies because either the activities are similar over all MHC technologies or information is unavailable to distinguish among the technologies. However, individual facilities could modify a BOA to best represent their unique situations. Table 4.21 presents costs to perform each of the critical tasks one time.

Table 4.20 BOAs for Transportation of Chemicals to MHC Line

Activities	Time (min)	Resources			Cost (\$/transport)
		Labor ^a	Materials ^b	Forklift ^c	
A. Paperwork and Maintenance					
1. Request for chemicals	2	\$0.34	\$0.10	\$0.00	\$0.44
2. Updating inventory logs	1	\$0.17	\$0.05	\$0.00	\$0.22
3. Safety and environmental record keeping	2	\$0.34	\$0.10	\$0.00	\$0.44
B. Move Forklift to Chemical Storage Area					
1. Move to forklift parking area	2	\$0.34	\$0.00	\$0.12	\$0.46
2. Prepare forklift to move chemicals	5	\$0.85	\$0.00	\$0.30	\$1.15
3. Move to line container storage area	2	\$0.34	\$0.00	\$0.12	\$0.46
4. Prepare forklift to move line container	3	\$0.51	\$0.00	\$0.18	\$0.69
5. Move forklift to chemical storage area	2	\$0.34	\$0.00	\$0.12	\$0.46
C. Locate Chemicals in Storage Area					
1. Move forklift to appropriate areas	1	\$0.17	\$0.00	\$0.06	\$0.23
2. Move chemical containers from storage to staging	2	\$0.34	\$0.00	\$0.12	\$0.46
3. Move containers from staging to storage	2	\$0.34	\$0.00	\$0.12	\$0.46
D. Preparation of Chemicals for Transfer					
1. Open chemical container(s)	1	\$0.17	\$0.05	\$0.00	\$0.22
2. Utilize correct tools to obtain chemicals	3	\$0.51	\$0.05	\$0.00	\$0.56
3. Place obtained chemicals in line container(s)	3	\$0.51	\$0.00	\$0.00	\$0.51
4. Close chemical container(s)	1.5	\$0.09	\$0.00	\$0.00	\$0.09
5. Place line container(s) on forklift	1	\$0.17	\$0.00	\$0.06	\$0.23
E. Transport Chemicals to Line					
1. Move forklift to line	2	\$0.34	\$0.00	\$0.12	\$0.46
2. Unload line container(s) at line	1	\$0.17	\$0.00	\$0.06	\$0.23
3. Move forklift to parking area	2	\$0.34	\$0.00	\$0.12	\$0.46
F. Transport Chemicals from Line to Bath					
1. Move line container(s) to bath	1	\$0.17	\$0.00	\$0.00	\$0.17
2. Clean line container(s)	2	\$0.34	\$0.20	\$0.00	\$0.54
3. Store line container(s) in appropriate area	1	\$0.17	\$0.00	\$0.00	\$0.17
Total Cost per Transport					\$9.11

^a Labor rate = \$10.22 per hour.^b Materials do not include chemicals or tools.^c Forklift operating cost = \$0.06 per minute.

Table 4.21 Costs of Critical Tasks

Task	Cost
Transportation of Chemicals	\$9.11
Tank Cleanup	\$67.00
Bath Setup	\$15.10
Sampling and Analysis	\$3.70
Filter Replacement	\$17.50

Fundamental Principles of Cost Analysis

Previous studies have defined seven principles of a fundamentally sound cost analysis (DeGamo et al., 1996), listed below. This analysis was designed to strictly adhere to these fundamental principles to increase the validity and credibility of the cost formulation.

Principle 1. Develop the alternatives to be considered: Table 4.13 identified the MHC technologies and equipment configurations considered in the cost analysis. Figure 4.13 listed the generic process steps and typical bath sequences for each of these technologies. These process steps and bath sequences are used consistently throughout the CTSA.

Principle 2. Focus on the difference between expected future outcomes among alternatives: Costs that are the same among all technologies do not need to be considered as there is no difference among alternatives for these costs. However, all costs that differ should be considered, provided the costs can be reliably estimated. Costs quantified in this analysis are capital costs, material costs, utility costs, wastewater costs, production costs, and maintenance costs. These cost categories were summarized earlier in this section and are discussed in more detail in Section 4.2.3.

Other cost categories are expected to differ in the future outcomes, but cannot be reliably estimated. These include waste treatment and disposal costs and quality costs. These costs were considered qualitatively earlier in this section.

Principle 3. Use a consistent viewpoint: The costs to produce a job consisting of 350,000 ssf are estimated for each technology and equipment configuration. Efficient MHC technologies with the ability to produce the 350,000 ssf quicker are rewarded by having the cost rates (i.e., \$/hr, etc.) of certain costs held constant, but the overall cost is calculated over a proportionally shorter time period. For example, if labor rates and the number of workers per day are the same, a process that takes 50 percent less time than the baseline to complete a job will have 50 percent lower labor costs than the baseline.

Principle 4. Use a common unit of measurement: Costs are normalized to a common unit of measurement, \$/ssf, to compare the relative costs of technologies.

Principle 5. Consider all relevant criteria: A thorough cost analysis requires the consideration of all criteria relevant to the overall costs of the technologies. The costs considered in this analysis were defined earlier in this section and are discussed in more detail in Section 4.2.3.

Principle 6. Make uncertainty explicit: Uncertainty is inherent in projecting the future outcomes of the alternatives and should be recognized in the cost analysis. Sensitivity analysis techniques are utilized to evaluate the effects of critical variables on cost.

Principle 7. Examine the analysis for accuracy: The cost analysis has been peer reviewed by industry, EPA, and other stakeholders to assess its accuracy and validity.

4.2.2 Simulation Results

Simulation models were run for each of the MHC processes. Three types of simulation outputs were obtained for use in the cost analysis:

- The duration and frequency of bath replacements.
- The production time required for each process.
- Down time incurred in producing 350,000 ssf.

The baseline process is used below as an example to explain the results of the simulation.

Table 4.22 presents the bath replacement simulation outputs. The values in the table represent the actual average time for bath replacement for the baseline process. Reviewing the table reveals that the cleaner/conditioner bath requires replacement nine times. Each replacement takes an average of 133 minutes. The total replacement time represents the total time the process is down due to bath replacements. Summing over all baths, bath replacement consumes 179 hours (10,760 minutes) when using the non-conveyorized electroless copper process to produce 350,000 ssf. Bath replacement simulation outputs for the other MHC processes are presented in Appendix G.

Table 4.22 Example Simulation Output for Non-Conveyorized Electroless Copper Process: Frequency and Duration of Bath Replacements

Chemical Bath	Frequency	Avg. Time/Replacement (minutes)	Total Time (minutes)
Cleaner/Conditioner	9	138	1,240
Microetch	18	146	2,630
Predip	8	125	1,000
Catalyst	1	230	230
Accelerator	16	130	2,080
Electroless Copper	10	114	1,140
Acid Dip	6	146	876
Anti-Tarnish	13	120	1,560
Total	81	133	10,760

As shown in the example, the bath replacement output value may be more than or less than the bath replacement input values reported in Tables 4.17 and 4.18. In this case, the input value for non-conveyorized electroless copper processes is 180 minutes, but the output values range from 114 to 230 minutes. Bath maintenance output values are less than input values when,

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on average, the bath is shut down with less than 180 minutes remaining in the shift. Under this scenario, the simulation model assumes that the employee will stay on past the end of the shift to complete the bath replacement. Thus, only the time remaining in a normal 8-hour shift is charged to down time.

Alternately, bath maintenance output values may be greater than input values if more than 180 minutes remain in the shift when the bath is shut down. In this case, the simulation model assumes that all racks or panels will clear the system prior to shutting down the line for a bath replacement. Thus, bath replacement times greater than 180 minutes account for the cycle time required for racks and/or panels to clear the system.

Table 4.23 presents the second and third types of simulation output, the total production time required for each process, and the down time incurred by each process in producing 350,000 ssf. Total production time is the sum of actual operating time and down time. Down time includes the 1.2 hours per day the line is assumed inactive plus the time the process is down for bath replacements. Again, actual simulation outputs are presented in Appendix G.

Table 4.23 Production Time and Down Time for MHC Processes to Produce 350,000 ssf

MHC Process	Total Production Time ^a		Total Down Time ^a	
	minutes	days	minutes	days
Electroless Copper, non-conveyorized (BASELINE)	163,500	401	33,900	83.2
Electroless Copper, conveyorized	36,100	88.4	16,300	40.0
Carbon, conveyorized	50,800	125	11,800	28.9
Conductive Polymer, conveyorized	29,100	71.3	7,110	17.4
Graphite, conveyorized	33,400	82.0	6,490	15.9
Non-Formaldehyde Electroless Copper, non-conveyorized	74,600	183	16,400	40.1
Organic-Palladium, non-conveyorized	31,800	77.9	10,800	26.4
Organic-Palladium, conveyorized	45,300	111	18,000	44.1
Tin-Palladium, non-conveyorized	48,500	119	13,600	33.4
Tin Palladium, conveyorized	26,100	63.9	9,010	22.1

^a To convert from minutes to days, divide by 6.8 hrs per day (408 minutes).

4.2.3 Cost Formulation Details and Sample Calculations

This section develops and describes in detail the cost formulation used for evaluating the MHC processes. The overall cost was calculated from individual cost categories that are common to, but expected to vary with, the MHC process alternatives. The cost model was validated by cross-referencing the cost categories with Tellus Institute (White et al., 1992), and Pacific Northwest Pollution Prevention Research Center (Badgett et al., 1995).

The cost model for an MHC alternative is as follows:

$$TC = C + M + U + WW + P + MA$$

where:

TC	= total cost to produce 350,000 ssf
C	= capital cost
M	= material cost
U	= utility cost
WW	= wastewater cost
P	= production cost
MA	= maintenance cost

The unit cost of producing 350,000 ssf is then represented as follows:

$$\text{Unit Cost (\$/ssf)} = \text{TC (\$)} / 350,000 \text{ ssf}$$

The following sections presents a detailed description of cost calculation methods together with sample calculations for the baseline non-conveyorized electroless copper process. Finally, the results of the sample calculations are summarized and then combined to calculate the total cost and unit cost for the non-conveyorized electroless copper process.

Capital Costs

This section presents methods and sample calculations for calculating capital costs. Capital costs are one-time or periodic costs incurred in the purchase of equipment or facilities. In this analysis, capital costs include the costs of primary equipment, equipment installation, and facility space utilized by the process. Primary equipment is the equipment vital to the operation of the MHC process without which the process would not be able to operate (i.e., bath tanks, heaters, rinse water system, etc.). Installation costs include costs to install the process equipment and prepare it for production. Facility space is the floor space required to operate the MHC process.

Total capital costs for the MHC technologies were calculated as follows:

$$C = (E + I + F) \times UR$$

where:

E	= annualized capital cost of equipment (\$/yr)
I	= annualized capital cost of installation (\$/yr)
F	= annualized capital cost of facility (\$/yr)
UR	= utilization ratio, defined as the time in days required to manufacture 350,000 ssf divided by one operating year (250 days)

The UR adjusts annualized costs for the amount of time required to process 350,000 ssf, determined from the simulation models of each process alternative. The components of capital costs are discussed further below followed by sample calculations of capital costs.

Equipment and Installation Costs. Primary equipment and installation costs estimates were provided by equipment suppliers and include delivery of equipment and sales tax.

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Equipment estimates were based on basic, no frills equipment capable of processing 100 panels/hr. Equipment estimates did not include auxiliary equipment such as statistical process control or automated sampling equipment sometimes found on MHC process lines.

Annual costs for both the equipment and installation costs were calculated assuming 10-year, straight-line depreciation of equipment and no salvage value. These annual costs were calculated using the following equations:

$$\begin{aligned} E &= \text{equipment cost (\$)} \div 10 \text{ years} \\ I &= \text{installation cost (\$)} \div 10 \text{ years} \end{aligned}$$

Facility Costs. Facility costs are capital costs for the floor space required to operate the MHC line. Facility costs were calculated assuming industrial floor space costs \$65/ft² and the facility is depreciated over 25 years using straight-line depreciation. The cost per square foot of floor space applies to Class A light manufacturing buildings with basements. This value was obtained from the Marshall Valuation Service (Vishanoff, 1995) and mean square foot costs (Ferguson, 1996). Facility costs were calculated using the following equation:

$$F = [\text{unit cost of facility utilized (\$/ft}^2\text{)} \times \text{footprint area/process step (ft}^2\text{/step)} \times \text{number of steps}] \div 25 \text{ years}$$

The “footprint area” is the area of floor space required by MHC equipment, plus a buffer zone to maneuver equipment or have room to work on the MHC process line.¹ The footprint area per process step was calculated by determining the footprint dimensions of each process alternative, adjusting the dimensions for working space, and then determining the area per process step. Because the footprint area depends on the type of process automation, the average dimensions of both conveyORIZED (5 ft x 38 ft) and non-conveyORIZED (6 ft x 45 ft) processes were determined from IPC Workplace Practices Questionnaire data. Since these dimensions account for the equipment footprint only, an additional 8 ft was added to every dimension to allow space for line operation, maintenance, and chemical handling. The floor space required by either equipment type was calculated (1,134 ft² for conveyORIZED processes and 1,342 ft² for non-conveyORIZED processes) and used to determine the area required per process step. This was done by first identifying the process alternative with the fewest process steps for each automation type, and then dividing the required floor space by that number of steps. This method conservatively estimated the amount of floor space required per process step for conveyORIZED processes at 160 ft²/step and for non-conveyORIZED processes at 110 ft²/step. The overall area required for each MHC alternative was then calculated using the following equations:

ConveyORIZED:

$$F_C = [\$65/\text{ft}^2 \times 160 \text{ ft}^2/\text{step} \times \text{number of steps per process}] \div 25 \text{ years}$$

Non-conveyORIZED:

$$F_N = [\$65/\text{ft}^2 \times 110 \text{ ft}^2/\text{step} \times \text{number of steps per process}] \div 25 \text{ years}$$

¹ PWB manufacturers and their suppliers use the term “footprint” to refer to the dimensions of process equipment, such as the dimensions of the MHC process line.

Sample Capital Costs Calculations. This section presents sample capital costs calculations for the baseline process. From Figure 4.13, the non-conveyorized electroless copper process consists of 19 chemical bath and rinse steps. Simulation outputs in Table 4.23 indicate this process takes 401 days to manufacture 350,000 ssf of PWB. Equipment vendors estimated equipment and installation costs at \$400,000 and \$70,000, respectively (Microplate, 1996; Coates ASI, 1996; PAL Inc., 1996; Circuit Chemistry, 1996; Western Technology Associates, 1996). The components of capital costs are calculated as follows:

$$\begin{aligned} E &= \$400,000 \div 10 \text{ yrs} = \$40,000/\text{yr} \\ I &= \$70,000 \div 10 \text{ yrs} = \$7,000/\text{yr} \\ F_N &= (\$65/\text{ft}^2 \times 110 \text{ ft}^2/\text{step} \times 19 \text{ steps}) \div 25 \text{ yrs} = \$5,430/\text{yr} \\ UR &= 401 \text{ days} \div 250 \text{ days/yr} = 1.60 \text{ yrs} \end{aligned}$$

Thus, the capital costs for the non-conveyorized electroless copper process to produce 350,000 ssf of PWB are as follows:

$$C = (\$40,000/\text{yr} + \$7,000/\text{yr} + \$5,430/\text{yr}) \times 1.60 \text{ yrs} = \$83,900$$

Materials Costs

Materials costs were calculated for the chemical products consumed in MHC process lines through the initial setup and subsequent replacement of process chemical baths. The following presents equations for calculating materials costs and sample materials cost calculations for the baseline process.

Materials Cost Calculation Methods. Chemical suppliers were asked to provide estimates of chemical costs (\$/ssf) early in the project. While some suppliers furnished estimates for one or more of their process alternatives, several suppliers did not provide chemical cost estimates for all of their MHC process lines being evaluated. Still others provided incomplete cost estimates or did not provide any supporting documentation of assumptions used to estimate chemical costs. Therefore, these data could not be used in the comparative cost estimates. Instead, chemical costs were estimated using the methods detailed below.

Chemical baths are typically made-up of one or more separate chemical products mixed together at specific concentrations to form a chemical solution. As PWBs are processed by the MHC line, the chemical baths become contaminated or depleted and require chemical additions on replacement. Baths are typically replaced according to analytical results or by supplier recommended replacement criteria specific to each bath. When the criteria are met or exceeded, the spent bath is removed and a new bath is created. The chemical cost to replace a specific bath one time is the sum of the costs of each chemical product in the bath and is given by the following equation:

$$\text{Chemical cost/bath replacement} = \sum_i [\text{chemical product cost/bath } (\$/\text{gal}) \times \% \text{ chemical product in bath} \times \text{total volume of bath (gal)}]$$

where:

$$i = \text{number of chemical products in a bath}$$

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The University of Tennessee Department of Industrial Engineering contacted suppliers to obtain price quotes in \$/gallon or \$/lb for MHC chemical products. The compositions of the individual process baths were determined from Product Data Sheets for each bath. The average volume of a chemical bath for non-conveyorized processes was calculated to be 75 gallons from IPC Workplace Practices Questionnaire data. For conveyorized processes, however, conveyor speed is constant, thus, the volume of chemicals in a bath varies by bath type to provide the necessary contact time (see Table 4.16 for conveyorized process bath volumes). These data were used in the above equation to calculate the chemical cost per bath replacement for each product line. The bath replacement costs were then averaged across like product lines (i.e., chemical costs from various suppliers of electroless copper processes were averaged by bath type, etc.) to determine an average chemical cost per replacement for each process bath.

To obtain the total materials cost, the chemical cost per bath replacement for each bath was multiplied by the number of bath replacements required (determined by simulation) and then summed over all the baths in an alternative. The cost of chemical additions was not included since no data were available to determine the amount and frequency of chemical additions. Materials costs are given by the following equation:

$$M = \sum_j [\text{chemical cost/bath replacement (\$)} \times \text{number of replacements/bath}]$$

where:

$$j = \text{number of baths in a process}$$

The frequency of replacement for individual process baths was determined using supplier recommended criteria provided on Product Data Sheets and from IPC Workplace Practices Questionnaire data. Simulation models were used to determine the number of times a bath would be replaced while an MHC line processes 350,000 ssf of PWB. Appendix G presents bath replacement criteria used in this analysis and summaries of chemical product cost by supplier and by MHC technology.

Sample Materials Cost Calculations. Table 4.24 presents an example of chemical costs per bath replacement for one supplier's electroless copper line. Similar costs are presented in Appendix G for the six electroless copper chemical product lines evaluated. The chemical costs per process bath for all six processes were averaged to determine the average chemical cost per bath for the non-conveyorized electroless copper process.

The chemical cost per bath was then calculated by multiplying the average chemical cost for a bath by the number of bath replacements required to process 350,000 ssf. The costs for each bath were then summed to give the total materials cost for the overall non-conveyorized electroless copper process. Table 4.25 presents the chemical cost per bath replacement, the number of bath replacements required as determined by simulation, the total chemical cost per bath, and the total material cost for the non-conveyorized electroless copper process. Similar material cost calculations for each of the MHC process alternatives are presented in Appendix G.

Table 4.24 Chemical Cost per Bath Replacement for One Supplier of the Non-Conveyorized Electroless Copper Process

Bath	Chemical Product	Product Cost ^a (\$)	Percentage of Chemical Product ^b	Chemical Cost/Bath Replacement ^c (\$)
Cleaner/Conditioner	A	\$25.45/gal	6	\$115
Microetch	B	\$2.57/lb	13.8 g/l	\$59
	C	\$7.62/gal	2.5	
	D	\$1.60/gal	18.5	
Predip	E	\$1.31/lb	31.7 g/l	\$22
	F	\$2.00/gal	1.5	
Catalyst	G	\$391.80/gal	4	\$1,186
	H	\$1.31/lb	0.17 g/l	
	I	\$2.00/gal	3.5	
Accelerator	J	\$18.10/gal	20	\$273
Electroless Copper	K	\$27.60/lb	7	\$252
	L	\$16.45/gal	8.5	
	M	\$4.50/gal	0.22	
Neutralizer	N	\$1.60/gal	100	\$120
Anti-Tarnish	O	\$39.00/gal	0.25	\$7

^a Product cost from supplier of the chemical product.

^b The percentage of a chemical product in each process bath was determined from Product Data Sheets provided by the supplier of the chemical product.

^c Cost per bath calculated assuming bath volumes of 75 gallons.

Table 4.25 Materials Cost for the Non-Conveyorized Electroless Copper Process

Bath	Chemical Cost/Bath Replacement ^a	Number of Bath Replacements ^b	Total Chemical Cost
Cleaner/Conditioner	\$188	9	\$1,690
Microetch	\$66	18	\$1,190
Predip	\$340	8	\$2,720
Catalyst	\$1,320	1	\$1,320
Accelerator	\$718	16	\$11,500
Electroless Copper	\$317	10	\$3,170
Neutralizer	\$120	6	\$720
Anti-Tarnish	\$16	13	\$208
Total Materials Cost			\$22,500^c

^a Reported data represents the chemical cost per bath replacement averaged over six electroless copper product lines.

^b Number of bath replacements required to process 350,000 ssf determined by simulation.

^c Does not include cost of chemical additions.

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Utility Costs

Utility costs for the MHC process include water consumed by rinse tanks,² electricity used to power the panel transportation system, heaters and other process equipment, and natural gas consumed by drying ovens employed by some MHC alternatives. The utility cost for the MHC process was determined as follows:

$$U = W + E + G$$

where:

- W = cost of water consumed (\$/ssf) to produce 350,000 ssf
- E = cost of electricity consumed (\$/ssf) to produce 350,000 ssf
- G = cost of natural gas consumed (\$/ssf) to produce 350,000 ssf

The following presents utility costs calculation methods and sample utility costs for the baseline process.

Utility Cost Calculation Methods. The rate of water consumption depends on both the number of distinct water rinse steps and the flow rate of the water in those steps. The typical number of water rinse steps for each MHC alternative was determined using supplier provided data together with data from the IPC Workplace Practices Questionnaire. Cascaded rinse steps were considered as one rinse step when calculating water consumption since the cascaded rinse steps all utilize the same water. Based on IPC Workplace Practices Questionnaire data, the average water flow rate for individual rinse steps was estimated at 1,185 gals/tank for conveyORIZED processes and 1,840 gals/tank for non-conveyORIZED processes. However, it was assumed that the rinse steps are shut off during periods of process down time. Therefore, daily water consumption rates were adjusted for the percentage of time the process was in operation.

The cost of water was calculated by multiplying the water consumption rate of the MHC process by the production time required to produce 350,000 ssf of PWB, and then applying a unit cost factor to the total. Water consumption rates for MHC alternatives are presented in Section 5.1, Resource Conservation, while production times were determined from the simulation models. A unit cost of \$1.60/1,000 gallons of water was obtained from the *Pollution Prevention and Control Survey* (EPA, 1995a). Following is the equation for calculating water cost:

$$W = \text{quantity of rinse water consumed (gal)} \times \$1.60/1,000 \text{ gal}$$

The rate of electricity consumption for each MHC alternative depends upon the equipment required to operate each alternative. Differences in required process equipment such as the number of heaters, pumps, and type and extent of panel agitation directly affect electricity consumption. The cost of electricity is calculated by multiplying the electricity consumption rate of the MHC process by the production time required to produce 350,000 ssf of PWB, and then applying a unit cost factor to the total. Electricity consumption rates for MHC alternatives are

² Water is also used in MHC chemical baths to dilute chemical products to the appropriate concentration, but this use of water was assumed negligible compared to the water consumed in rinse tanks.

presented in Section 5.2, Energy Impacts, while the required production time was determined by simulation. A unit cost of \$0.0473/kW-hr was obtained from the International Energy Agency. Therefore, the energy cost was calculated using the following equation:

$$E = \text{hourly consumption rate (kW)} \times \text{required production time (hrs)} \times \$0.0473/\text{kW-hr}$$

Natural gas is utilized to fire the drying ovens required by both the graphite and carbon MHC alternatives. The amount of gas consumed was determined by multiplying the natural gas consumption rate for the MHC process by the amount of operating time required by the process to produce 350,000 ssf of PWB and then applying a unit cost to the result. Knoxville Utilities Board (KUB) charges \$0.3683 per therm of natural gas consumed (KUB, 1996a). Thus, the cost of natural gas consumption was calculated by the following equation:

$$G = \text{natural gas consumption rate (therm/hr)} \times \text{required production time (hrs)} \times \$0.3683/\text{therm}$$

The graphite process typically requires a single drying stage while the carbon process requires two drying oven stages. Natural gas consumption rates in cubic feet per hour for both carbon (180 cu.ft./hr) and graphite (90 cu.ft./hr) processes were obtained from Section 5.2, Energy Impacts. The production time required to produce 350,000 ssf of PWB came from simulation results.

Sample Utility Cost Calculations. The above methodology was used to calculate the utility costs for each of the MHC alternatives. This section presents sample utility cost calculations for the non-conveyorized electroless copper process.

Simulation results indicate the non-conveyorized electroless copper process is down 83.2 days and takes 401 days overall (at 6.8 hrs/day) to produce 350,000 ssf. It is comprised of seven rinse steps which consume approximately 4.1 million gallons of water during the course of the job (see Section 5.1, Resource Conservation). Electricity is consumed at a rate of 27.2 kW/hr (see Section 5.2, Energy Impacts). The non-conveyorized electroless copper process has no drying ovens and, therefore, does not use natural gas. Based on this information, water, electricity, and gas costs were calculated as follows:

$$\begin{aligned} W &= 4,089,000 \text{ gallons} \times \$1.60/1,000 \text{ gals} = \$6,540 \\ E &= 27.2 \text{ kW} \times (401 \text{ days} - 83.2 \text{ days}) \times 6.8 \text{ hrs/day} \times \$0.0473/\text{kW-hr} = \$2,780 \\ G &= \$0 \end{aligned}$$

Thus, the utility cost for the non-conveyorized electroless copper process was determined by the calculation:

$$U = \$6,540 + \$2,780 + \$0 = \$9,320$$

Wastewater Costs

Wastewater Cost Calculation Methods. Wastewater costs for the MHC processes were only determined for the cost of discharging wastewater to a POTW. The analysis assumes that discharges are made in compliance with local allowable limits for chemical concentrations and other parameters so that no fines are incurred.

Wastewater quantities were assumed equal to the quantity of rinse water used. Rinse water usage was calculated in Section 5.1, Resource Conservation, and used to calculate water costs in the Utility Costs section. The unit costs for fees charged by a POTW for both city and non-city discharges of wastewater were obtained from KUB and averaged for use in calculating wastewater cost (KUB, 1996b). These average unit costs are not flat rates applied to the total wastewater discharge, but rather combine to form a tiered cost scale that applies an incremental unit cost to each level of discharge. The tiered cost scale for wastewater discharges to a POTW is presented in Table 4.26.

Table 4.26 Tiered Cost Scale for Monthly Wastewater Discharges to a POTW

Wastewater Discharge Quantity (ccf/month)	City Discharge Cost (\$/ccf/month)	Non-City Discharge Cost (\$/ccf/month)	Average Discharge Cost (\$/ccf/month)
0 - 2	\$6.30	\$7.40	\$6.85
3 - 10	\$2.92	\$3.21	\$3.06
11 - 100	\$2.59	\$2.85	\$2.72
101 - 400	\$2.22	\$2.44	\$2.33
401 - 5,000	\$1.85	\$2.05	\$1.95

Source: KUB, 1996b.

ccf: 100 cubic ft.

The unit costs displayed for each level of discharge are applied incrementally to the quantity of monthly discharge. For example, the first two cubic feet of wastewater discharged in a month are assessed a charge of \$6.85, while the next eight cubic feet cost \$3.06, and so on. The production time required to produce 350,000 ssf of PWB comes from the simulation models. Thus, wastewater costs were calculated as follows:

$$WW = \sum_i [\text{quantity of discharge in tier (ccf/mo)} \times \text{tier cost factor (\$/ccf)}] \times \text{required production time (months)}$$

where:

i = number of cost tiers
ccf = 100 cubic ft

Sample Wastewater Cost Calculations. This section presents sample wastewater calculations for the non-conveyorized electroless copper process. Based on rinse water usage, the total wastewater release was approximately 4.1 million gallons. The required production time in months was calculated using the required production time from Table 4.23 and a 250 day operating year ($401 \text{ days} \div 250 \text{ days/year} \times 12 \text{ months/yr} = 19.2 \text{ months}$). Thus, the monthly

wastewater release was 285 ccf (4,089,000 gallons \div 19.2 months \div 748 gal/hundred cu ft). To calculate the wastewater cost for the non-conveyorized electroless copper process, the tiered cost scale was applied to the quantity of discharge and the resulting costs per tier were summed, as follows:

$$\begin{aligned} \$6.85 \times 2 \text{ ccf/month} &= \$13.70 \text{ ccf/month} \\ \$3.06 \times 8 \text{ ccf/month} &= \$24.48 \text{ ccf/month} \\ \$2.72 \times 90 \text{ ccf/month} &= \$245 \text{ ccf/month} \\ \$2.33 \times 185 \text{ ccf/month} &= \$431 \text{ ccf/month} \end{aligned}$$

$$\text{Monthly discharge cost} = \$13.70 + \$24.48 + \$245 + \$431 = \$714/\text{month}$$

The monthly cost was then multiplied by the number of months required to produce 350,000 ssf of PWB to calculate the overall wastewater treatment cost:

$$\text{WW} = \$714/\text{month} \times 19.2 \text{ month} = \$13,700$$

Production Costs

Production Cost Calculation Methods. Production costs for the MHC process include both the cost of labor required to operate the process and the cost of transporting chemicals to the production line from storage. Production costs were calculated by the following equation:

$$P = LA + TR$$

where:

$$\begin{aligned} LA &= \text{production labor cost (\$/ssf) to produce 350,000 ssf} \\ TR &= \text{chemical transportation cost (\$/ssf) to produce 350,000 ssf} \end{aligned}$$

Production labor cost is a function of the number and type of employees and the length of time required to complete a job. The calculation of production labor cost assumes that line operators perform all of the daily activities, excluding bath maintenance, vital to the operation of the MHC process. Labor costs associated with bath maintenance activities, such as sampling and analysis, are presented in the discussion of maintenance costs, below. An average number of line operators was determined for both conveyorized (one line operator) and non-conveyorized (1.1 line operators) processes from IPC Workplace Practices Questionnaire data and supported by site visit observations. Although no significant difference in the number of line operators by automation type was reported in the data, the number of line operators for non-conveyorized processes was adjusted upward to 1.1 to reflect the greater level of labor content for these processes as compared to conveyorized processes.

The labor time required to complete the specified job (350,000 ssf) was calculated assuming an average shift time of eight hours per day and using the number of days required to produce 350,000 ssf of PWB from simulation results. A labor wage of \$10.22/hr was obtained from the American Wages and Salary Survey (Fisher, 1995) and utilized for MHC line operators. Therefore, labor costs for MHC alternatives were calculated as follows:

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$$LA = \text{number of operators} \times \$10.22/\text{hr} \times 8 \text{ hrs/day} \times \text{required production time (days)}$$

The production cost category of chemical transportation cost includes the cost of transporting chemicals from storage to the MHC process line. A BOA, presented in Appendix G, was developed and used to calculate the unit cost per chemical transport. Since chemicals are consumed whenever a bath is replaced, the number of trips required to supply the process line with chemicals equals the number of bath replacements required to produce 350,000 ssf of PWB. Chemical transportation cost was calculated as follows:

$$TR = \text{number of bath replacements} \times \text{unit cost per chemical transport (\$)}$$

Sample Production Cost Calculations. For the example of the non-conveyorized electroless copper process, production labor cost was calculated assuming 1.1 operators working for 401 days (see Table 4.23). Chemical transportation cost was calculated based on a cost per chemical transport of \$9.11 (see Table 4.20 and Appendix G) and 81 bath replacements (see Table 4.22). Thus, the production cost was calculated as follows:

$$\begin{aligned} LA &= 1.1 \times \$10.22 \times 8 \text{ hrs/day} \times 401 \text{ days} = \$36,100 \\ TR &= 81 \times \$9.11 = \$737 \end{aligned}$$

thus:

$$P = \$36,100 + \$737 = \$36,800$$

Maintenance Costs

Maintenance Costs Calculation Methods. The maintenance costs for the MHC process include the costs associated with tank cleaning, bath setup, sampling and analysis of bath chemistries, and bath filter replacement. Maintenance costs were calculated as follows:

$$MA = TC + BS + FR + ST$$

where:

$$\begin{aligned} TC &= \text{tank cleanup cost (\$/ssf) to produce 350,000 ssf} \\ BS &= \text{bath setup cost (\$/ssf) to produce 350,000 ssf} \\ FR &= \text{filter replacement cost (\$/ssf) to produce 350,000 ssf} \\ ST &= \text{sampling cost (\$/ssf) to produce 350,000 ssf} \end{aligned}$$

The maintenance costs listed above depend on the unit cost per repetition of the activity and the number of times the activity was performed. For each maintenance cost category, a BOA was developed to characterize the cost of labor, materials, and tools associated with a single repetition of that activity. The BOA and unit cost per repetition for each cost category are presented in Appendix G. It was assumed that the activities and costs characterized on the BOAs are the same regardless of the MHC process or process baths. Unit costs per repetition for both tank cleanup and bath setup were determined to be \$67.00 and \$15.10, respectively.

The number of tank cleanups and bath setups equals the number of bath replacements obtained from process simulation results (see Appendix G). Each time a bath is replaced, the tank is cleaned before a replacement bath is created. The costs of tank cleanup and bath setup are thus given by the following:

$$\begin{aligned} \text{TC} &= \text{number of tank cleanups} \times \$67.00 \\ \text{BS} &= \text{number of bath setups} \times \$15.10 \end{aligned}$$

IPC Workplace Practices Questionnaire data for both filter replacement and bath sampling and analysis were reported in occurrences per year instead of as a function of throughput. Ninetieth percentile values were calculated from these data and used in dermal exposure estimates in Section 3.2, Exposure Assessment. These frequencies were adjusted for this analysis using the URs for the production time required to manufacture 350,000 ssf of PWB. Using the unit costs determined by the BOAs developed for filter replacement (\$17.50 per replacement) and bath sampling and testing (\$3.70 per test), the costs for these maintenance activities were calculated as follows:

$$\begin{aligned} \text{FR} &= \text{annual number of filter replacement} \times \text{UR} \times \$17.50 \\ \text{ST} &= \text{annual number of sampling \& testing} \times \text{UR} \times \$3.70 \end{aligned}$$

The total maintenance cost for each MHC process alternative was determined by first calculating the individual maintenance costs using the above equations and then summing the results.

Maintenance Costs Sample Calculations. This section presents sample maintenance costs calculations for the non-conveyorized electroless copper process. From Table 4.23, this process has a production time of 401 days, which gives a UR of 1.60 ($\text{UR} = 401 \div 250$). The number of tank cleanups and bath setups equals the number of bath replacements reported in Table 4.22 (81 bath replacements). As reported in Section 3.2, Exposure Assessment, chemical baths are sampled and tested 720 per year and filters are replaced 100 times per year. Thus, the maintenance costs for the non-conveyorized electroless copper process are:

$$\begin{aligned} \text{TC} &= 81 \times \$67.00 = \$5,430 \\ \text{BS} &= 81 \times \$15.10 = \$1,220 \\ \text{ST} &= 720 \times 1.60 \times \$3.70 = \$4,260 \\ \text{FR} &= 100 \times 1.60 \times \$17.50 = \$2,800 \end{aligned}$$

therefore:

$$\text{MA} = \$5,430 + \$1,220 + \$4,260 + \$2,800 = \$13,700$$

Determination Total Cost and Unit Cost

The total cost for MHC process alternatives was calculated by summing the totals of the individual costs categories. The unit cost (UC), or cost per ssf of PWB produced, can then be calculated by dividing the total cost by the amount of PWBs produced. Table 4.27 summarizes

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the total cost of manufacturing 350,000 ssf of PWB using the non-conveyorized electroless copper process.

The UC for the non-conveyorized electroless copper process was then calculated as follows:

$$\begin{aligned}\text{UC} &= \text{total cost (TC)} \div 350,000 \text{ ssf} \\ &= \$180,000 \div 350,000 \text{ ssf} \\ &= \$0.51/\text{ssf}\end{aligned}$$

Table 4.27 Summary of Costs for the Non-Conveyorized Electroless Copper Process

Cost Category	Component	Component Cost	Totals
Capital Cost	Primary Equipment	\$64,000	
	Installation	\$11,200	
	Facility	\$8,690	\$83,900
Material Cost	Chemical(s)	\$22,500	\$22,500
Utility Cost	Water	\$6,540	
	Electricity	\$2,780	
	Natural Gas	\$0	\$9,320
Wastewater Cost	Wastewater Discharge	\$13,700	\$13,700
Production Cost	Transportation of Material	\$737	
	Labor for Line Operation	\$36,100	\$36,800
Maintenance Cost	Tank Cleanup	\$5,430	
	Bath Setup	\$1,220	
	Sampling and Analysis	\$4,260	
	Filter Replacement	\$2,800	\$13,700
Total Cost			\$180,000

4.2.4 Results

Table 4.28 presents the costs for each of the MHC technologies. Table 4.29 presents unit costs (\$/ssf). The total cost of producing 350,000 ssf ranged from a high of \$180,000 for the non-conveyorized electroless copper process to a low of \$33,500 for the conveyorized conductive polymer process. Corresponding unit costs ranged from \$0.51/ssf for the baseline process to \$0.09/ssf for the conveyorized conductive polymer process. With the exception of the non-conveyorized, non-formaldehyde electroless copper process, all of the alternatives cost at least 50 percent less than the baseline. Both conveyorized and non-conveyorized equipment configurations were costed for the electroless copper, tin-palladium, and organic-palladium MHC alternatives. For the electroless copper technology, the conveyorized process was much more economical than the non-conveyorized process. Less difference in unit cost was seen between the tin-palladium technologies (\$0.12/ssf for conveyorized processes and \$0.14/ssf for non-conveyorized processes) and the organic-palladium technologies (\$0.17/ssf for conveyorized processes and \$0.15/ssf for non-conveyorized processes). Non-conveyorized processes are, on average, more expensive (\$0.30) than conveyorized systems (\$0.16).

Total cost data in Table 4.28 illustrate that chemical cost is typically the largest cost (in nine out of ten MHC processes) followed by equipment cost (in one out of ten MHC processes). The high costs of the baseline process appear to be primarily due to the length of time it took this process to produce 350,000 ssf (4,015 days). This is over twice as long as that required by the next process (183 days for non-conveyorized, non-formaldehyde electroless copper).

Table 4.28 Total Cost of MHC Alternatives

Cost Category	Cost Components	Electroless Copper, non-conveyorized	Carbon, conveyorized	Conductive Polymer, conveyorized
Capital Cost	Primary Equipment	\$64,000	\$7,470	\$5,560
	Installation	\$11,200	\$299	\$0
	Facility	\$8,690	\$2,690	\$2,250
Material Cost	Chemical(s)	\$22,500	\$32,900	\$10,400
Utility Cost	Water	\$6,540	\$725	\$410
	Electricity	\$2,780	\$836	\$460
	Natural Gas	\$0	\$418	\$0
Wastewater Cost	Wastewater Discharge	\$13,700	\$1,710	\$965
Production Cost	Transportation of Material	\$737	\$446	\$673
	Labor for Normal Production	\$36,100	\$10,200	\$5,830
Maintenance Cost	Tank Cleanup	\$5,430	\$3,280	\$4,960
	Bath Setup	\$1,220	\$740	\$1,120
	Sampling and Testing	\$4,260	\$405	\$436
	Filter Replacement	\$2,800	\$116	\$376
Total Cost		\$180,000	\$62,200	\$33,400

Cost Category	Cost Components	Electroless Copper, conveyorized	Graphite, conveyorized	Non-Formaldehyde Electroless Copper, non-conveyorized
Capital Cost	Primary Equipment	\$6,190	\$3,580	\$29,300
	Installation	\$212	\$131	\$5,120
	Facility	\$2,800	\$1,090	\$3,350
Material Cost	Chemical(s)	\$22,600	\$59,800	\$69,600
Utility Cost	Water	\$642	\$251	\$2,100
	Electricity	\$669	\$462	\$1,310
	Natural Gas	\$0	\$145	\$0
Wastewater Cost	Wastewater Discharge	\$1,450	\$612	\$4,520
Production Cost	Transportation of Material	\$883	\$319	\$682
	Labor for Normal Production	\$7,230	\$6,700	\$16,200
Maintenance Cost	Tank Cleanup	\$6,500	\$2,350	\$5,030
	Bath Setup	\$1,460	\$529	\$1,130
	Sampling and Testing	\$942	\$316	\$691
	Filter Replacement	\$612	\$901	\$214
Total Cost		\$52,200	\$77,200	\$139,200

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Table 4.28 Total Cost of MHC Alternatives (cont.)

Cost Category	Cost Components	Organic-Palladium, conveyorized	Organic-Palladium, non-conveyorized
Capital Cost	Primary Equipment	\$5,780	\$4,160
	Installation	\$356	\$256
	Facility	\$2,220	\$1,100
Material Cost	Chemical(s)	\$28,900	\$27,000
Utility Cost	Water	\$635	\$758
	Electricity	\$720	\$325
	Natural Gas	\$0	\$0
Wastewater Cost	Wastewater Discharge	\$1,510	\$1,670
Production Cost	Transportation of Material	\$1,260	\$1,050
	Labor for Normal Production	\$6,530	\$7,190
Maintenance Cost	Tank Cleanup	\$9,250	\$7,710
	Bath Setup	\$2,080	\$1,740
	Sampling and Testing	\$411	\$288
	Filter Replacement	\$271	\$385
Total Cost		\$59,900	\$53,700

Cost Category	Cost Components	Tin-Palladium, conveyorized	Tin-Palladium, non-conveyorized
Capital Cost	Primary Equipment	\$1,280	\$4,760
	Installation	\$205	\$381
	Facility	\$1,490	\$1,910
Material Cost	Chemical(s)	\$25,500	\$22,300
Utility Cost	Water	\$317	\$1,010
	Electricity	\$468	\$635
	Natural Gas	\$0	\$0
Wastewater Cost	Wastewater Discharge	\$754	\$2,340
Production Cost	Transportation of Material	\$537	\$455
	Labor for Normal Production	\$5,230	\$10,700
Maintenance Cost	Tank Cleanup	\$3,950	\$3,350
	Bath Setup	\$891	\$755
	Sampling and Testing	\$493	\$916
	Filter Replacement	\$332	\$616
Total Cost		\$41,400	\$50,100

Table 4.29 MHC Alternative Unit Costs

MHC Alternative	Production (ssf/yr)	Total Cost (\$)	Unit Cost (\$/ssf)
Electroless Copper, non-conveyorized (BASELINE)	350,000	\$180,000	\$0.51
Carbon, conveyorized	350,000	\$62,200	\$0.18
Conductive Polymer, conveyorized	350,000	\$33,400	\$0.09
Electroless Copper, conveyorized	350,000	\$52,200	\$0.15
Graphite, conveyorized	350,000	\$77,200	\$0.22
Non-Formaldehyde Electroless Copper, non-conveyorized	350,000	\$139,200	\$0.40
Organic-Palladium, conveyorized	350,000	\$59,900	\$0.17
Organic-Palladium, non-conveyorized	350,000	\$53,700	\$0.15
Tin-Palladium, conveyorized	350,000	\$41,400	\$0.12
Tin-Palladium, non-conveyorized	350,000	\$50,100	\$0.14

4.2.5 Sensitivity Analysis

This section presents the results of sensitivity analyses to determine the effects of critical variables on overall costs. Three separate sensitivity analyses were performed, including sensitivity analyses to determine the following:

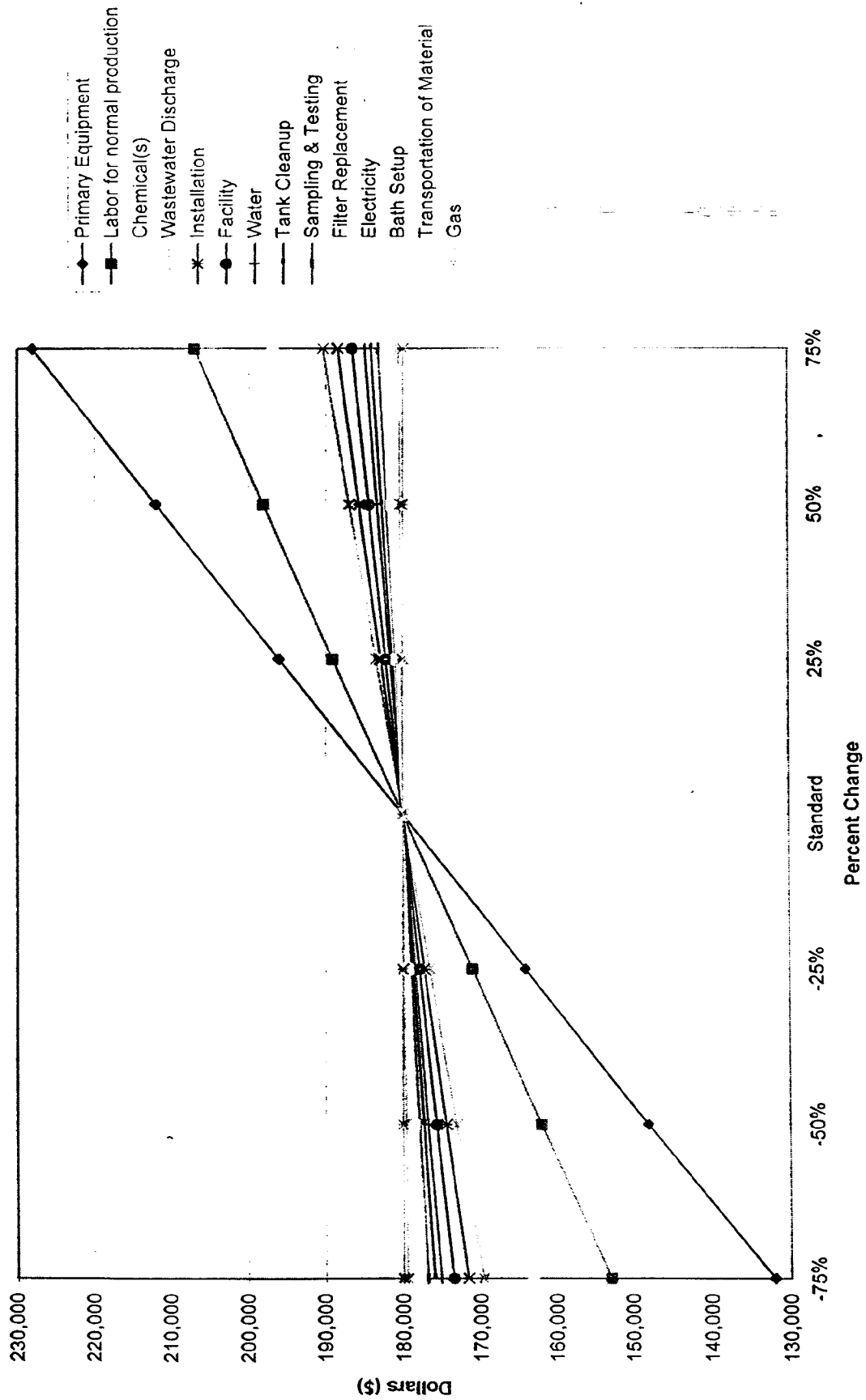
- The effects of the various cost components on the overall cost of the alternatives.
- The effects of down time on the cost of the baseline process.
- The effects of water consumption on the cost of the baseline process.

To determine the effects of the various cost components on overall cost, each cost component was increased and decreased by 25 percent, 50 percent and 75 percent, and an overall cost was calculated. Figure 4.15 presents the results of this sensitivity analysis for the baseline process. Appendix G presents the results of this type of sensitivity analysis for the alternatives. The results indicate two groupings of cost components: 1) those that have little impact on the overall cost; and 2) those which have significant impact on the overall cost of an MHC alternative. The first category includes tank cleanup, electricity, filter replacement, sampling and analysis, bath setup, transportation, and natural gas costs. The second category includes equipment, labor, and chemical costs.

To determine the effects of down time on the overall cost of the baseline process, the duration of bath replacements was reduced by 33 percent and 67 percent. Both the 33 and 67 percent reductions led to a less than one percent reduction in overall cost. These results indicate the effects of down time on overall costs are small.

Water consumption was also reduced by 33 percent and 67 percent to determine its effects on the overall cost of the baseline process. Reducing water consumption affects both water costs and wastewater discharge costs. Reducing water consumption by 33 percent resulted in an overall cost reduction of 2.8 percent, while reducing water consumption by 67 percent reduced the overall cost by 5.9 percent.

Figure 4.15 Sensitivity Analysis for the Non-ConveyORIZED Electroless Copper Process



4.2.6 Conclusions

This analysis developed comparative costs for seven MHC technologies, including electroless copper, conductive polymer, carbon, graphite, non-formaldehyde electroless copper, organic-palladium, and tin-palladium processes. Costs were developed for each technology and equipment configuration for which data were available from the IPC Workplace Practices Questionnaire and Performance Demonstration, for a total of ten processes (four non-conveyorized processes and six conveyorized processes). Costs were estimated using a hybrid cost model which combines traditional costs with simulation modeling and activity-based costs. The cost model was designed to determine the total cost of processing a specific amount of PWBs through a fully operational MHC line, in this case 350,000 ssf. The cost model does not estimate start-up costs for a facility switching to an MHC alternative. Total costs were divided by the throughput (350,000 ssf) to determine a unit cost in \$/ssf.

The cost components considered include capital costs (primary equipment, installation, and facility costs), materials costs (limited to chemical costs), utility costs (water, electricity, and natural gas costs), wastewater costs (limited to wastewater discharge cost), production costs (production labor and chemical transport costs), and maintenance costs (tank cleanup, bath setup, sampling and analysis, and filter replacement costs). Other cost components may contribute significantly to overall costs, but were not quantified because they could not be reliably estimated. These include wastewater treatment cost, sludge recycling and disposal cost, other solid waste disposal costs, and quality costs.

Based on the results of this analysis, all of the alternatives are more economical than the non-conveyorized electroless copper process. In general, conveyorized processes cost less than non-conveyorized processes. Costs ranged from \$0.51/ssf for the baseline process to \$0.09/ssf for the conveyorized conductive polymer process. Seven process alternatives cost less than \$0.20/ssf (conveyorized carbon at \$0.18/ssf, conveyorized conductive polymer at \$0.09/ssf, conveyorized electroless copper at \$0.15/ssf, non-conveyorized organic palladium at \$0.15/ssf, conveyorized organic-palladium at \$0.17/ssf, and conveyorized and non-conveyorized tin-palladium at \$0.12/ssf and \$0.14/ssf, respectively). Three processes cost more than \$0.20/ssf (non-conveyorized electroless copper at \$0.51/ssf, non-conveyorized non-formaldehyde electroless copper at \$0.40/ssf, and conveyorized graphite at \$0.22/ssf).

Chemical cost was the single largest component cost for nine of the ten processes. Equipment cost was the largest cost for one process. Three separate sensitivity analyses of the results indicated that chemical cost, production labor cost, and equipment cost have the greatest effect on the overall cost results.